Acceleration Data Structures for Ray Tracing

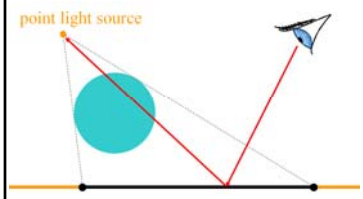
Thanks to Fredo Durand and Barb Cutler

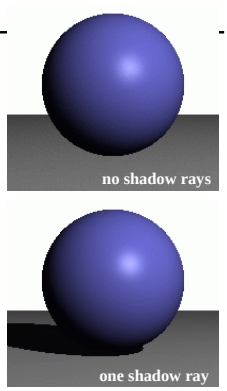
Ray-tracing Acceleration

- Motivation – Distribution Ray Tracing
  - Soft shadows
  - Antialiasing (getting rid of jaggies)
  - Glossy reflection
  - Motion blur
  - Depth of field (focus)
- Bounding Boxes
- Spatial Acceleration Data Structures
- Flattening the Transformation Hierarchy

Shadows

- one shadow ray per intersection per point light source





Shadows & Light Sources

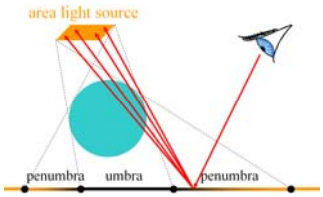

http://3media.initialized.org/photos/2000-10-18/index_gall.htm

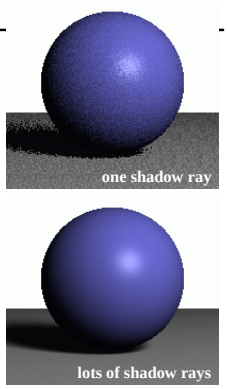

http://www.davidfay.com/index.php

http://www.pa.uky.edu/~sciworks/light/preview/bulb2.htm

Soft Shadows

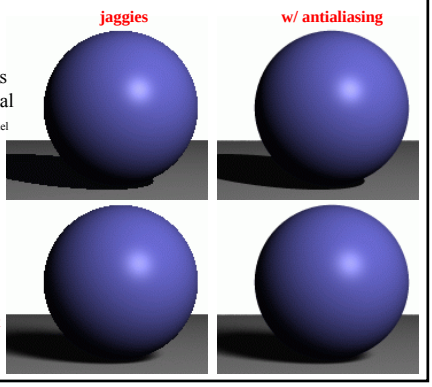
- Multiple shadow rays to sample area light source
- Distribute rays over an interval – light source





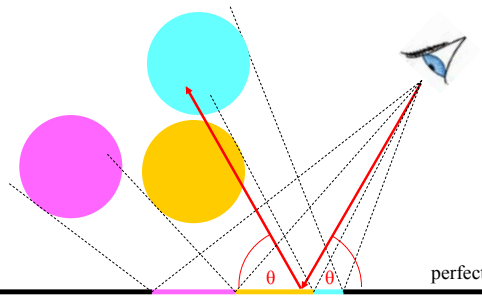
Antialiasing – Supersampling

- Multiple rays per pixel
- Distribute rays over an interval – multiple rays per pixel



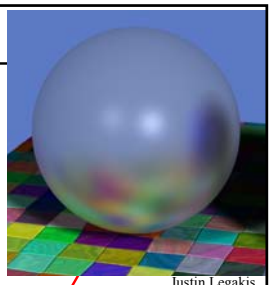
Reflection

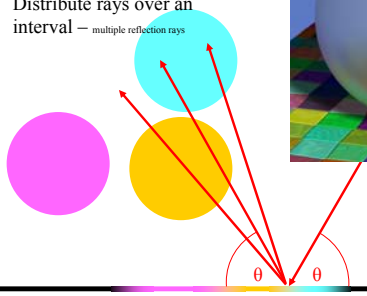
- one reflection ray per intersection



Glossy Reflection

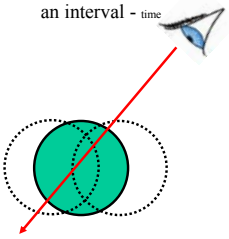
- multiple reflection rays
- Distribute rays over an interval – multiple reflection rays


Justin Legakis



Motion Blur

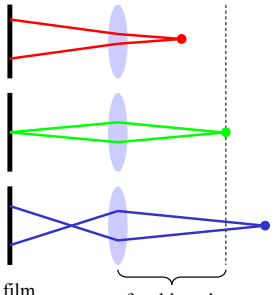
- Sample objects temporally
- Distribute rays over an interval - time

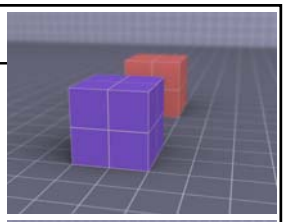


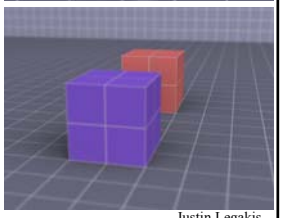

Rob Cook

Depth of Field

- Distribute rays over an interval - lens area






Justin Legakis

Ray Tracing Algorithm Analysis

- Ray casting
- Lots of primitives
- Recursive
- Distributed Ray Tracing Effects
  - Soft shadows
  - Anti-aliasing
  - Glossy reflection
  - Motion blur
  - Depth of field

cost ≈ height * width *
num primitives *
intersection cost *
size of recursive ray tree *
num shadow rays *
num supersamples *
num glossy rays *
num temporal samples *
num focal samples *
. . .

can we reduce this?

Ray-Tracing Taxonomy

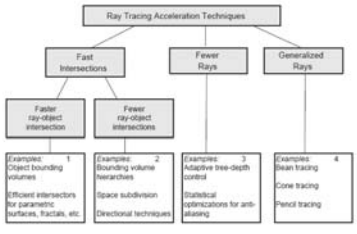


Figure 1: A broad classification of acceleration techniques.

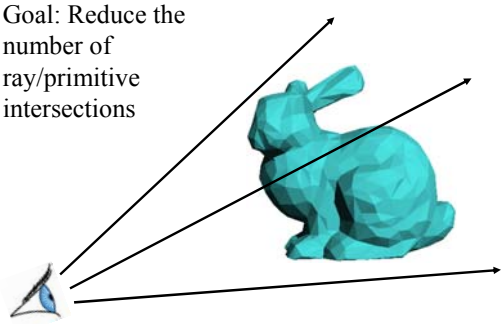
by James Arvo and David Kirk

Ray-tracing Acceleration

- Motivation – Distribution Ray Tracing
- Bounding Boxes
  - of each primitive
  - of groups
  - of transformed primitives
- Spatial Acceleration Data Structures
- Flattening the Transformation Hierarchy

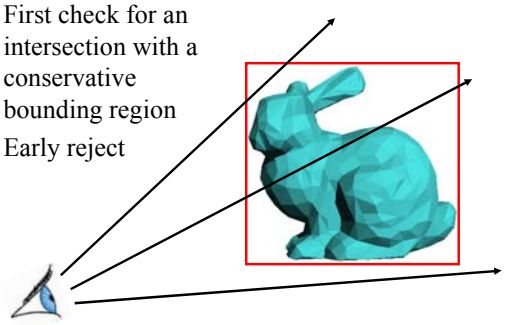
Acceleration of Ray Casting

- Goal: Reduce the number of ray/primitive intersections



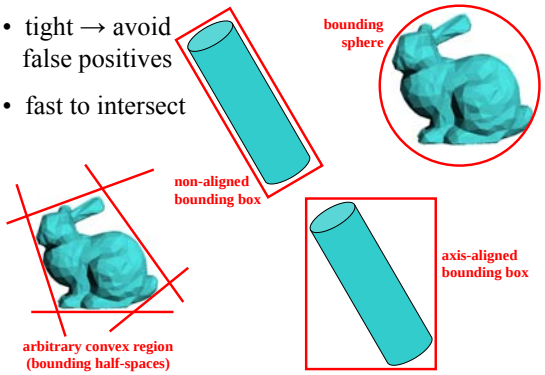
Conservative Bounding Region

- First check for an intersection with a conservative bounding region
- Early reject

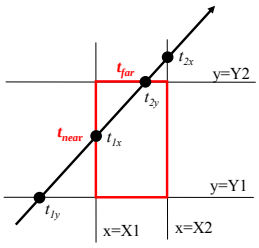


Conservative Bounding Regions

- tight → avoid false positives
- fast to intersect

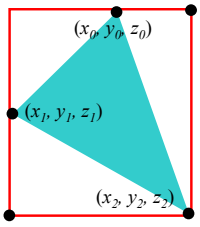


Intersection with Axis-Aligned Box



- For all 3 axes, calculate the intersection distances t_1 and t_2
- $t_{near} = \max(t_{1x}, t_{1y}, t_{1z})$
  $t_{far} = \min(t_{2x}, t_{2y}, t_{2z})$
- If $t_{near} > t_{far}$, box is missed
- If $t_{far} < t_{min}$, box is behind
- If box survived tests, report intersection at t_{near}

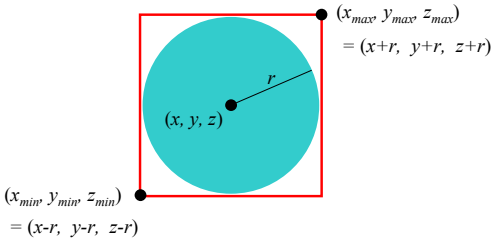
Bounding Box of a Triangle



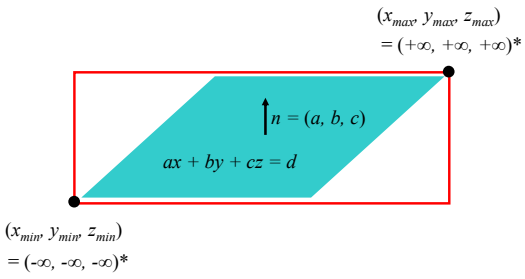
$(x_{max}, y_{max}, z_{max})$
$= (\max(x_0,x_1,x_2),$
$\max(y_0,y_1,y_2),$
$\max(z_0,z_1,z_2))$

$(x_{min}, y_{min}, z_{min})$
$= (\min(x_0,x_1,x_2),$
$\min(y_0,y_1,y_2),$
$\min(z_0,z_1,z_2))$

Bounding Box of a Sphere

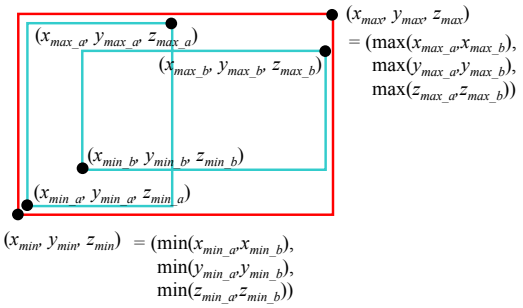


Bounding Box of a Plane

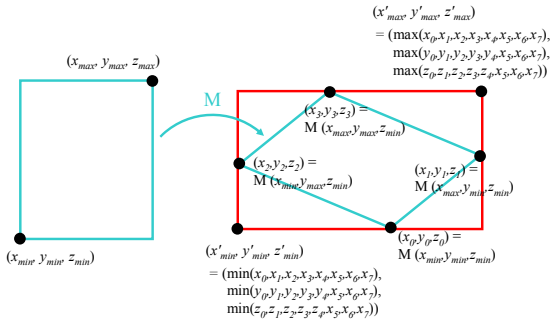


* unless n is exactly perpendicular to an axis

Bounding Box of a Group

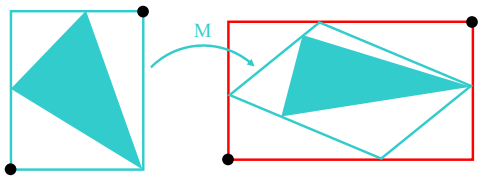


Bounding Box of a Transform

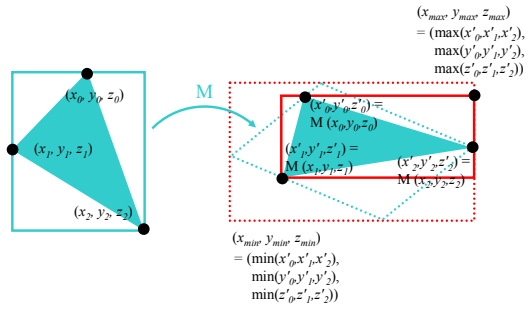


Special Case: Transformed Triangle

Can we do better?



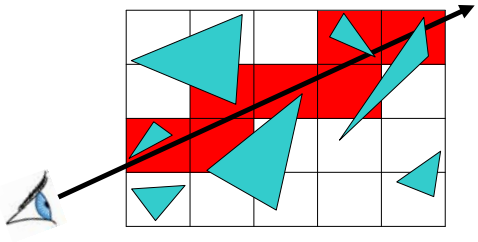
Special Case: Transformed Triangle



Ray-tracing Acceleration

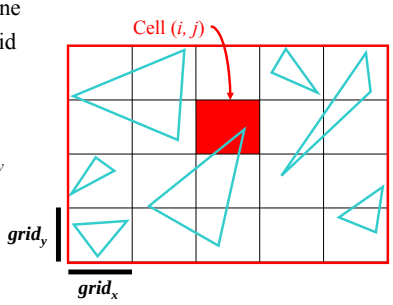
- Motivation – Distribution Ray Tracing
- Bounding Boxes
- Spatial Acceleration Data Structures
  - Regular Grid
  - Adaptive Grids
  - Hierarchical Bounding Volumes
- Flattening the Transformation Hierarchy

Regular Grid



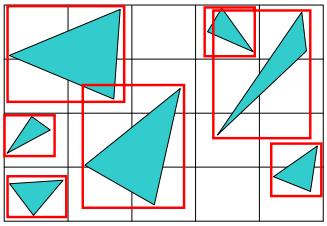
Create Grid

- Find bounding box of scene
- Choose grid resolution (n_x, n_y, n_z)
- $grid_x$ need not = $grid_y$



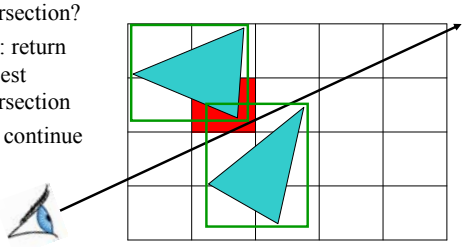
Insert Primitives into Grid

- Primitives that overlap multiple cells?
- Insert into multiple cells (use pointers)



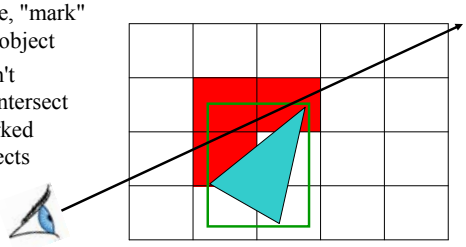
For Each Cell Along a Ray

- Does the cell contain an intersection?
- Yes: return closest intersection
- No: continue



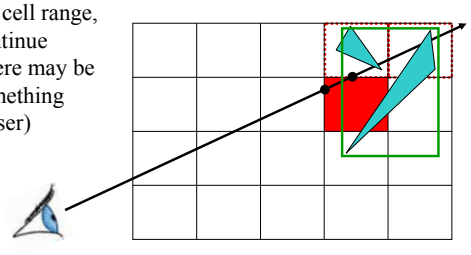
Preventing Repeated Computation

- Perform the computation once, "mark" the object
- Don't re-intersect marked objects



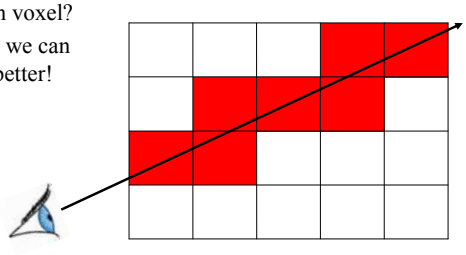
Don't Return Distant Intersections

- If intersection t is not within the cell range, continue (there may be something closer)



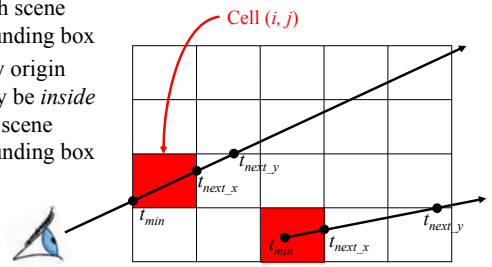
Which Cells Should We Examine?

- Should we intersect the ray with each voxel?
- No! we can do better!



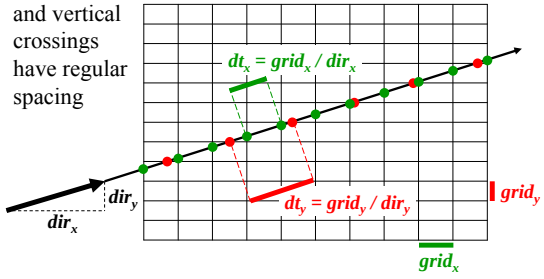
Where Do We Start?

- Intersect ray with scene bounding box
- Ray origin may be *inside* the scene bounding box



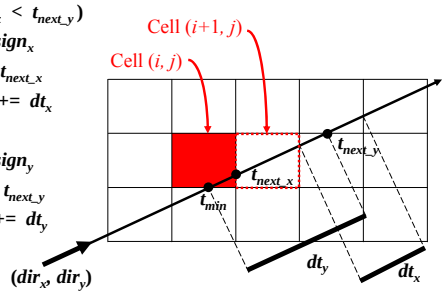
Is there a Pattern to Cell Crossings?

- Yes, the horizontal and vertical crossings have regular spacing



What's the Next Cell?

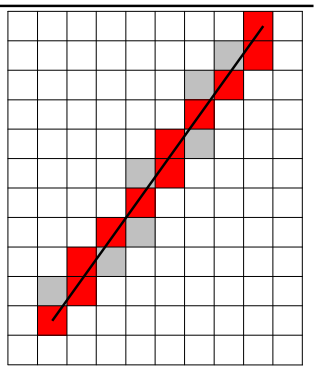
if $(t_{next\_x} < t_{next\_y})$
  i += $sign_x$
  $t_{min} = t_{next\_x}$
  t_{next_x} += dt_x
else
  j += $sign_y$
  $t_{min} = t_{next\_y}$
  t_{next_y} += dt_y



if $(dir_x > 0)$ $sign_x = 1$ *else* $sign_x = -1$
if $(dir_y > 0)$ $sign_y = 1$ *else* $sign_y = -1$

What's the Next Cell?

- 3DDDA – Three Dimensional Digital Difference Analyzer
- Similar to Bresenham's Line Rasterization!



Pseudo-Code

```
create grid
insert primitives into grid
for each ray r
  find initial cell c(i,j), t_min, t_next_x & t_next_y
  compute dt_x, dt_y, sign_x and sign_y
  while c != NULL
    for each primitive p in c
      intersect r with p
      if intersection in range found
        return
    c = find next cell
```

Regular Grid Discussion

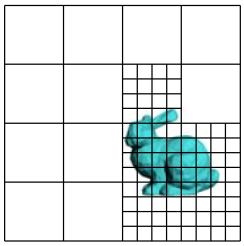
- Advantages?
  - easy to construct
  - easy to traverse
- Disadvantages?
  - may be only sparsely filled
  - geometry may still be clumped

Ray-tracing Acceleration

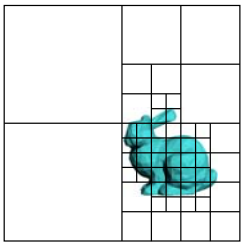
- Motivation – Distribution Ray Tracing
- Bounding Boxes
- Spatial Acceleration Data Structures
  - Regular Grid
  - Adaptive Grids
  - Hierarchical Bounding Volumes
- Flattening the Transformation Hierarchy

Adaptive Grids

- Subdivide until each cell contains no more than *n* elements, or maximum depth *d* is reached



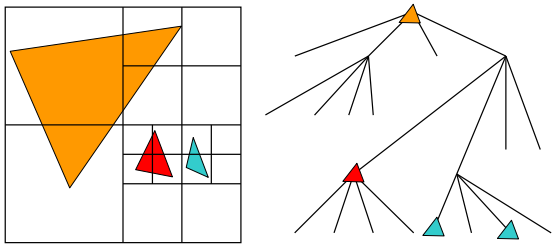
Nested Grids



Octree/(Quadtree)

Primitives in an Adaptive Grid

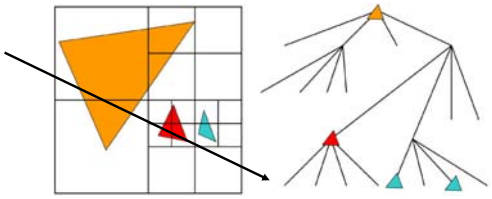
- Can live at intermediate levels, or be pushed to lowest level of grid



Octree/(Quadtree)

Adaptive Grid Discussion

- Advantages?
  - grid complexity matches geometric density
- Disadvantages?
  - more expensive to traverse (especially octree)

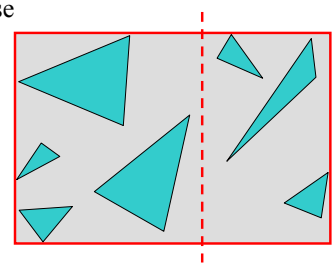


Ray-tracing Acceleration

- Motivation – Distribution Ray Tracing
- Bounding Boxes
- Spatial Acceleration Data Structures
  - Regular Grid
  - Adaptive Grids
  - Hierarchical Bounding Volumes
- Flattening the Transformation Hierarchy

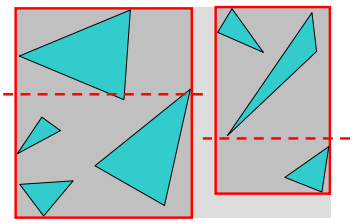
Bounding Volume Hierarchy

- Find bounding box of objects
- Split objects into two groups
- Recurse



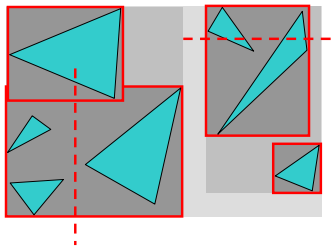
Bounding Volume Hierarchy

- Find bounding box of objects
- Split objects into two groups
- Recurse



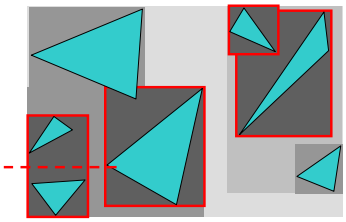
Bounding Volume Hierarchy

- Find bounding box of objects
- Split objects into two groups
- Recurse



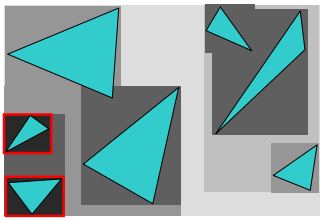
Bounding Volume Hierarchy

- Find bounding box of objects
- Split objects into two groups
- Recurse



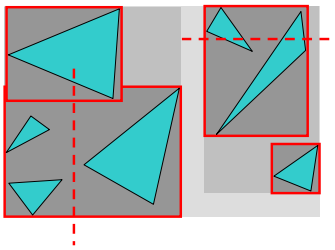
Bounding Volume Hierarchy

- Find bounding box of objects
- Split objects into two groups
- Recurse



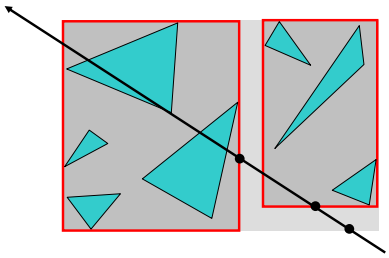
Where to split objects?

- At midpoint *OR*
- Sort, and put half of the objects on each side *OR*
- Use modeling hierarchy



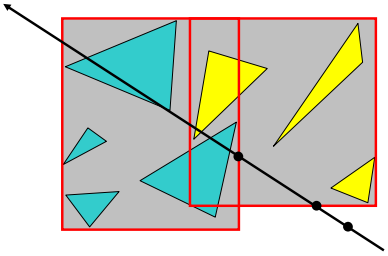
Intersection with BVH

- Check sub-volume with closer intersection first



Intersection with BVH

- Don't return intersection immediately if the other subvolume may have a closer intersection



Bounding Volume Hierarchy Discussion

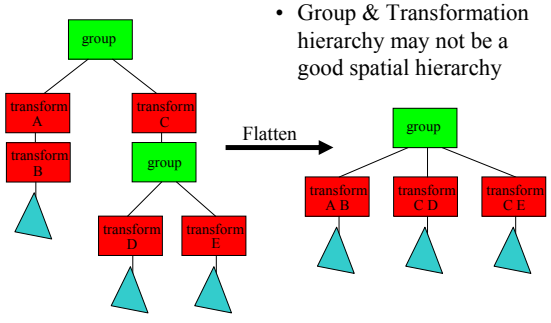
- Advantages
  - easy to construct
  - easy to traverse
  - binary
- Disadvantages
  - may be difficult to choose a good split for a node
  - poor split may result in minimal spatial pruning

Ray-tracing Acceleration

- Motivation – Distribution Ray Tracing
- Bounding Boxes
- Spatial Acceleration Data Structures
- Flattening the Transformation Hierarchy

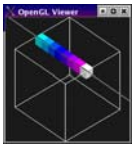
Transformation Hierarchy

- Group & Transformation hierarchy may not be a good spatial hierarchy

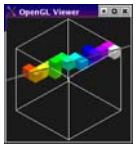


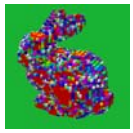
Ray Marching Visualization

sphere voxelization

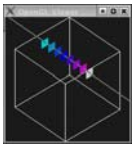


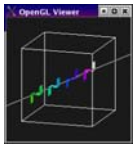
cells traversed



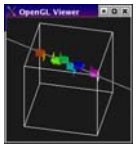


primitive density





entered faces



- Next time: ray-tracing at Pixar